ARMY RESEARCH LABORATORY

Welding of Electron Beam Single Melt Ti-6Al-4V Plate

by William S. de Rosset, Matthew Burkins, and Brijmohan Roopchand

ARL-MR-539

May 2002

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

ARL-MR-539 **May 2002**

Welding of Electron Beam Single Melt Ti-6Al-4V Plate

William S. de Rosset and Matthew Burkins
Weapons and Materials Research Directorate, ARL

Brijmohan Roopchand
U.S. Army Tank-automotive and Armaments Command, Armament Research, Development, and Engineering Center

Abstract

Single melt titanium alloy is being considered for use as armor in ground combat vehicles due to its lower cost relative to aerospace-grade material. This report examines welding issues associated with fabricating titanium alloy plate. In particular, the quality of welded single melt material was investigated as well as the possibility of out-of-position welding of standard titanium alloy. The initial results indicate that single melt material can be welded using standard techniques. Out-of-position welding can be accomplished under controlled conditions, but further process development would be needed to be able to repair titanium alloy armor in the field.

Acknowledgments

The authors wish to acknowledge the contributions to this work from many people. First, we are indebted to the technical skills of the welders that produced the final products described in the report: Bob Bruce of the U.S. Army Research Laboratory (ARL) Machine Shop and Tom Dymond of the U.S. Army Soldier Biological and Chemical Command (SBCCOM) Machine Shop. Wayne Zeigler was instrumental in getting the tensile specimens tested at the U.S. Army Aberdeen Test Center (ATC) Materials Testing Laboratory. Scott Grendahl, Marc Pepi, and Victor Champagne provided invaluable technical advice and guidance. Bill Green was responsible for making the digitized radiographs. Finally, thanks go to Eleanor Deal and her staff for the ballistic tests conducted on the welded plate.

INTENTIONALLY LEFT BLANK.

Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

List of Tables

INTENTIONALLY LEFT BLANK.

1. Background

As early as Fiscal Year 1995 (FY95), discussions began between the U.S. Army Research Laboratory (ARL) and Office of the Project Manager (OPM) Crusader to investigate state-of-the-art developments in titanium welding. As a result of those discussions, the following tasks were developed for execution by ARL:

- Task 1: Conduct gas metal arc weld (GMAW) (with Ti-6-2-1-1 filler metal) Ti-6Al-4V "I" plates of 1, 1 1/2, and 3 in; nondestructive and ballistic testing; bend, tensile, hardness, and macro test specimens; U.S. Army Tank-automotive and Armaments Command (TACOM) supplies plate and filler metal;
- Task 2: Conduct Ti-6Al-4V out-of-positioning welding using pulsed GMAW; double "V" butt joints in the vertical, horizontal, and overhead positions; mechanical and bend test specimens; weld repair on ballistically tested I plate (see Task 1) using out-of-position techniques developed;
- Task 3: Weld fabricate Ti-6Al-4V test section (armor box) for ballistic testing;
- Task 4: Conduct evaluation of former Soviet Union (FSU) welded (with fluxed-cored wire) commercially pure (CP) titanium plate; verify that the process may be used for battlefield damage repair; and
- Task 5: Compare titanium manufacturing costs (casting, forging, powder metallurgy [PM], etc.) to rolled homogeneous alloy (RHA) steel.

The motivation for this work was the application of titanium armor to the Crusader vehicle. In particular, the properties of electron beam single melt titanium, a relatively inexpensive form of titanium, were to be examined. The centerpiece of the work was task 3, the fabrication and ballistic testing of an armor box made of welded titanium. In the end, both ARL and General Dynamics Ground Systems fabricated and tested armor boxes. This work is complete, and the final report has been written (Grendahl et al. 2001). Task 4 has also been completed, and the report has been published (Snoha et al. 2001). In addition, the Edison Welding Institute has published a report under contract to ARL (Harris 2001). One of the objectives of this report was to develop a detailed welding procedure for repair of titanium alloy plate.

Several personnel changes have delayed the completion of the remainder of the tasks. In FY00, OPM Crusader inquired as to the status of the uncompleted tasks, and ARL responded by assigning a physical scientist to complete the work. The tasks were also modified to take into account further developments in this area. This report documents the results achieved in carrying out the remainder of the tasks.

2. Introduction

Titanium and its alloys have been used extensively by the aerospace industry because of titanium's high strength-to-weight ratio. The value of using this material for ground vehicles has also been recognized, especially in the area of ballistic protection. However, application of titanium to ground vehicles has been limited to small parts, such as the Bradley Fighting Vehicle's commander's hatch and appliqué armor, the M1 Abrams's turret blow-off panels and gunner's primary sight cover (Roopchand 2001a), and the Crusader gun mount (Roopchand 2001b). Reluctance to use titanium for larger structures can be attributed primarily to the high cost of titanium (relative to steel) and the uncertainty of the weld quality in joining thick sections of titanium in an armored structure. Another issue was how to field repair damaged sections of titanium armor.

The tasks proposed for this effort addressed all of these issues. Under task 3, a large armor box of welded titanium was fabricated and tested ballistically. Task 1, which should have preceded task 3, evolved to an investigation of welding single melt titanium alloy. The single melt titanium process provides a less expensive means to produce titanium. The idea here was to see if the welding technique used to make the armor box was applicable to the lower-cost single melt titanium. Tasks 2 and 4 were directed toward the problem of field repairing damaged titanium structures. Finally, task 5 was simply an attempt to quantify the difference in cost between steel and titanium.

This report provides the results of the work performed under tasks 1, 2, and 5. The report is divided into three major parts, each of which addresses a specific task.

3. Task 1

3.1 Procedures and Results

The purpose of this task was to reproduce the welding technique used to make the armor box fabricated in task 3 (see section 1) and apply it to the electron beam single melt material. In addition, mechanical and ballistic tests would be conducted to assess the strength of the welds. Electron beam single melt titanium has been shown to meet the mechanical requirements of MIL-T-9046J, Grade AB-1 (U.S. Department of Defense 1999) (Burkins et al. 2001). The chemical composition of the plates is shown in Table 1.

Table 1. Chemical composition of titanium plate (Burkins et al. 2001).

Element	Weight-Percent
Titanium	89.1
Aluminum	6.28
Vanadium	4.16
Oxygen	0.176
Iron	0.151
Trace Elements	Remainder

The chemical composition meets the American Society for Testing and Materials (ASTM) specification B265-99 (ASTM 1999) for Grade 5 titanium alloy; in addition, the ASTM specifications for yield strength (828 MPa) and tensile strength (895 MPa) are met by the single melt alloy plates.

Three different thicknesses of titanium plate stock (1, 1 1/2, and 2 1/2 in) were provided by TACOM for this task. In order to make an I plate out of a given thickness, two plates of dimensions 9 in × 18 ft were cut from the stock. For the 1- and 1 1/2-in-thick plates, a single 30° slant edge was machined on a 9-in edge. Two plates were then butted together with a 1/8-in gap between plates. The arrangement is shown schematically in Figure 1. This figure is not to scale. Note also that a 1/4- × 1-in strip of titanium was placed underneath the plates along the gap. This strip (not shown in Figure 1) acted as backup to the plates to keep the weld material confined between the plates for the first welding pass.

The configuration for the 2 1/2-in plate is shown in Figure 2. There was no backing plate used for this configuration.

All plates to be welded were clamped to a large metal welding table. This ensured electrical contact for the welding process as well as kept the plates from moving. The thin strip of titanium backing placed between the plates and welding table prevented the plates from lying flat on the table. Thus, before the weld was made the two plates were cocked at a small angle. As the weld material slowly cooled to room temperature, the weld material contracted. Residual thermal stresses caused the joined plates to rotate into a planar alignment. (Note that in task 2, the two plates started out aligned, but the thermal stresses caused the welded plate to form a shallow V shape.) The 2 1/2-in plate was welded alternatively on each side so that the thermal stresses were balanced out.

The surfaces to be welded were wiped down with acetone. The plates were not preheated prior to welding. The ends of each pair of plates were tack welded to prevent rotation of the plates as the bead was run. A stainless steel brush was used to remove scale from the tack welds. The brush was also used to remove scale after each bead was run. An Airco Pulse Arc 350 was used to make the

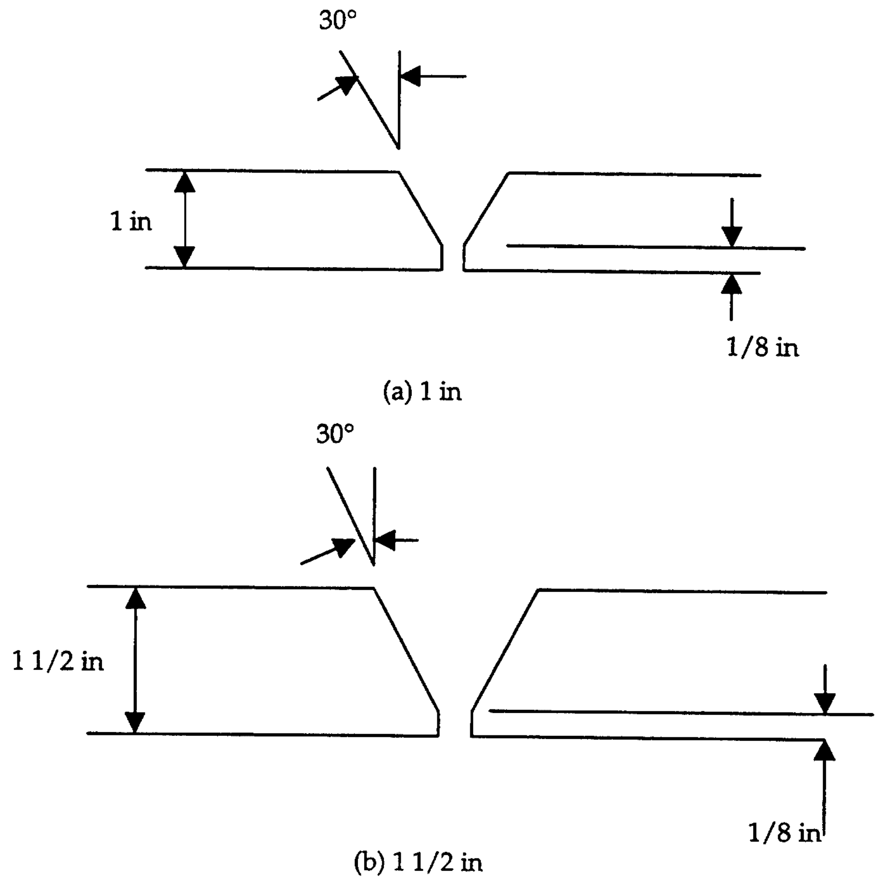

Figure 1. Weld configuration for the 1- and 1 1/2-in plates (not to scale).

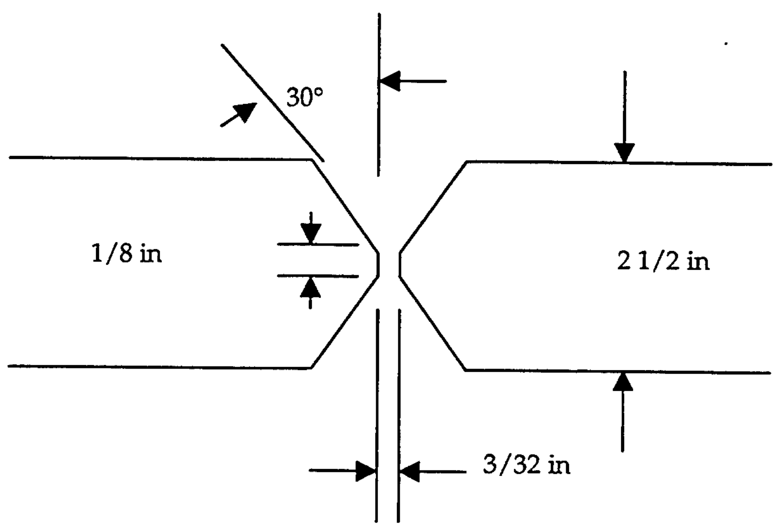

Figure 2. Weld configuration for the 2 1/2-in plate.

weld bead. Argon was used to shield the weld from the atmosphere. Welding wire designated Ti-6Al-4V extra-low interstitial (ELI) was used to make the weld. Its size was 0.045 in, and its composition was specified according to Aerospace Material Specification (AMS) 4956C (Society of Automotive Engineers 1994). After each bead was made, a Beckman Industrial 450 thermometer was used to measure the temperature of the weld area. The plates were allowed to cool below 150° F before the next pass was made.

The plates were welded to various degrees of completion by Robert Bruce of the ARL Machine Shop and left to cool for ~1 hr. When the welding procedure was resumed, it was noticed that cracks had begun to form in each of the plates after one pass. The cracks were first noticed in the 2 1/2-in plate first, followed by the 1 1/2-in plates, and then the 1-in plate. All cracks were perpendicular to the weld direction, and they were totally contained within the weld material. Each weld exhibited ~10 cracks. The weld in the 2 1/2-in plate cracked only on one side. The cracks in the 2 1/2- and 1 1/2-in plates spanned the entire weld. However, examination of the weld in the 1-in plate showed that the cracks were contained almost entirely in the last weld bead. An example of one of the cracks in the 1-in plate weld is shown in Figure 3. The last weld bead was also discolored and rough in appearance, unlike the smooth silvery appearance of the other beads.

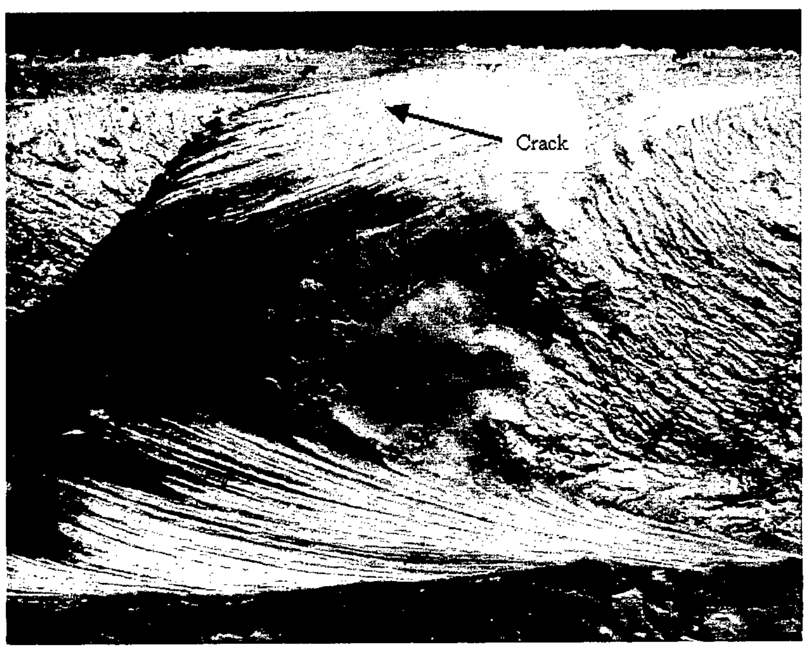

Figure 3. Crack in 1-in plate weld.

Welding experts were consulted on the probable cause of the cracking. The appearance of the last bead in the 1-in plate indicated that there had been some contamination of the metal pool while the weld was forming. This was likely caused by poor shielding with the trailing argon shield. Another possibility was

that the plates had not been preheated before the welding. The preheat treatment helps to drive off moisture from the surface of the plates and reduces the amount of oxygen and hydrogen contained in the weld material. A third possibility was that the welding wire that was used had not been properly stored. It had been over a year since the wire had been used to make the box, and during that time it had not been stored in an inert gas atmosphere. Consequently, there was the possibility that the wire had picked up oxygen and hydrogen as impurities.

The welding wire was subsequently chemically analyzed by Lehigh Testing Laboratories, New Castle, DE. The results are shown in Table 2.

Table 2. Chemical analysis of welding wire.

Element	Percentage
Aluminum	5.88
Vanadium	4.04
Oxygen	0.080
Nitrogen	0.003
Carbon	0.034
Iron	0.09
Hydrogen	0.0064
Silicon	0.02
Titanium	Remainder

The oxygen content appears to be within normal standards. However, the hydrogen content is about three times that normally found in this type of wire.

As a further check, a sample of weld material was taken from the 1 1/2-in plate and sent to Lehigh Testing Laboratories for chemical analysis. They found that the oxygen content was 0.12%, and the hydrogen content was 0.0026%. Note, however, that the sample was taken from the center of the weld and did not include material from the last weld bead.

The weld from the 1-in plate was removed, and the plate was remachined with the edge configuration as shown in Figure 4. This allowed welding on both sides of the plate and helped to balance out the thermal stresses. In removing the weld from the 1-in plate, the thermal stresses produced during the welding process were relieved, and all the cracks in the weld tended to close up.

New welding wire was purchased and stored in an argon atmosphere until ready for use. The surfaces of the 1-in plate were treated as before (ground with a silicon carbide disk grinder and washed with acetone). The two edges were overlapped by a very small amount. The plates were preheated to 125 °F with a torch. The plates were then tack welded at the ends and placed on an aluminum backing plate. Argon was introduced into the underside V channel, and a first pass was made. (Note that three gas bottles were used in the operation: one for

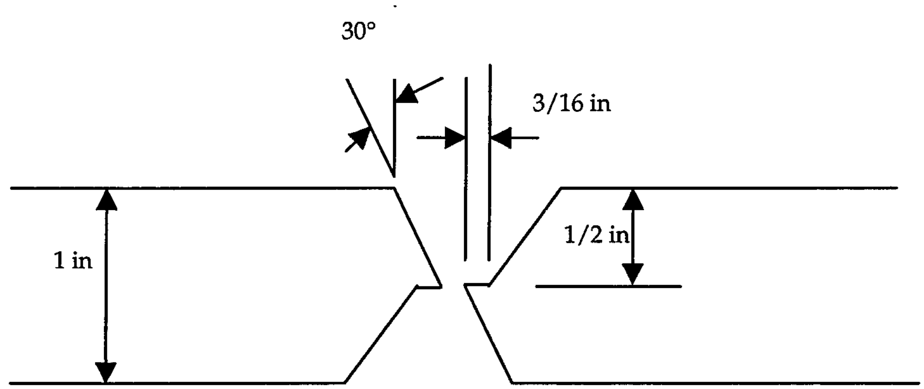

Figure 4. 1-in plate edge configuration.

the welding gun, one for the trailing shield, and one for the back shielding.) All other aspects of the welding process were the same as used previously, except that only the 1-in plate was welded, and the process was carried out to completion in one work session. Table 3 gives more specific details of the welding procedure.

Table 3. Welding parameters.

Process	Gas Metal Arc Weld
Mode	Semi-Automatic
Filler Metal	
Specification	AWS A5.16
Type	Ti-6Al-4V ELI
Diameter	0.045 in
Shielding Gas	
Type	Primary – Argon; Secondary – Argon; Backup – Argon
Flow Rate	(cubic feet per hour): 50/50/20
Cup/Nozzle Diameter	5/8 in
Welding Current (amperes)	300–310
Arc Voltage (volts)	32–35
Wire Feed Speed (inches per minute)	500
Electrode Stickout	1/2 in
Tip Recess	1/8 in
Interpass Temperature (maximum, degrees Fahrenheit)	150
Torch Progression	Forehand
Travel Angle	10°
Bead Type	Stringer

After ~3 in of weld bead had been laid down, the welding gun blew through the 3/16-in ledge. Welding was stopped and the situation assessed. It was decided

to go forward with the weld and come back to the blow-through section later. This was done, but the quality of the weld in this section was in question.

The plate was flipped and the weld material that had come through the blow-through section was ground away. From this point, the welding proceeded normally until the entire weld was completed with no cracks appearing on the surface.

The plate was x-rayed and examined for flaws. The radiograph for the welded plate is shown in Figure 5. The different shades of gray indicate thickness variations in the weld. There were no obvious defects other than some very minor inclusions noted in the middle of the plate. In particular, the section that experienced the blow-through appeared to be defect-free.

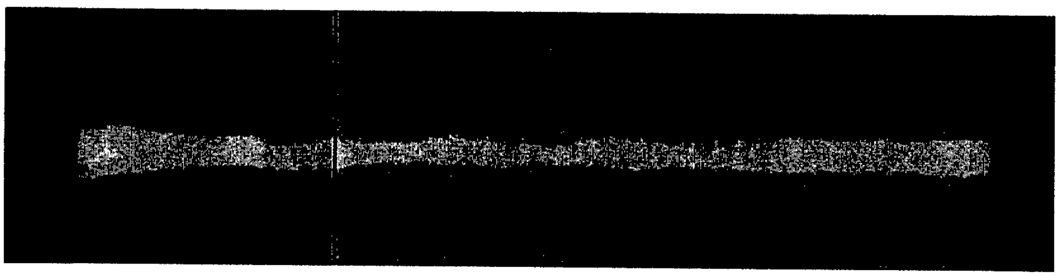

Figure 5. Radiograph of weld in 1-in plate.

Two tensile specimens were cut from the welded plate with the dimensions as shown in Figure 6 (not to scale). The specimens were cut from the portion of the weld that did not experience the blow-through problem.

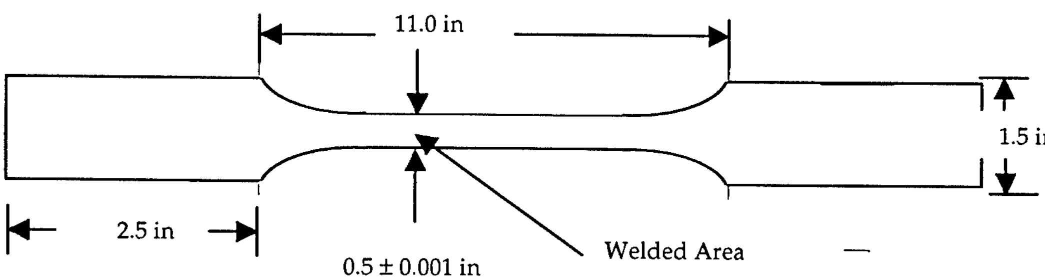

Figure 6. Tensile test specimen.

The sample thickness was 1 in. The weld was not ground to the plate thickness but was left in the as-welded condition. Both specimens were pulled to failure at the Materials Test Laboratory at the U.S. Army Aberdeen Test Center (ATC). The stress was applied transversely to the original rolling direction of the plate. The numerical results are given in Table 4.

Table 4. Tensile test results.

Specimen	Ultimate Tensile Strength (psi)	Yield Stress (psi)	% Elongation	Modulation (ksi)
1	117	116	1.05	16,100
2	131	126	1.28	14,300

Specimen 1 failed through the weld. There did not appear to be good fusion in the center of the weld, where the failure probably started. Figure 7 shows both fracture surfaces of the tensile specimen. The very dark center (vertical) portion in the center of the picture is the region of the weld where the break appears to have originated.

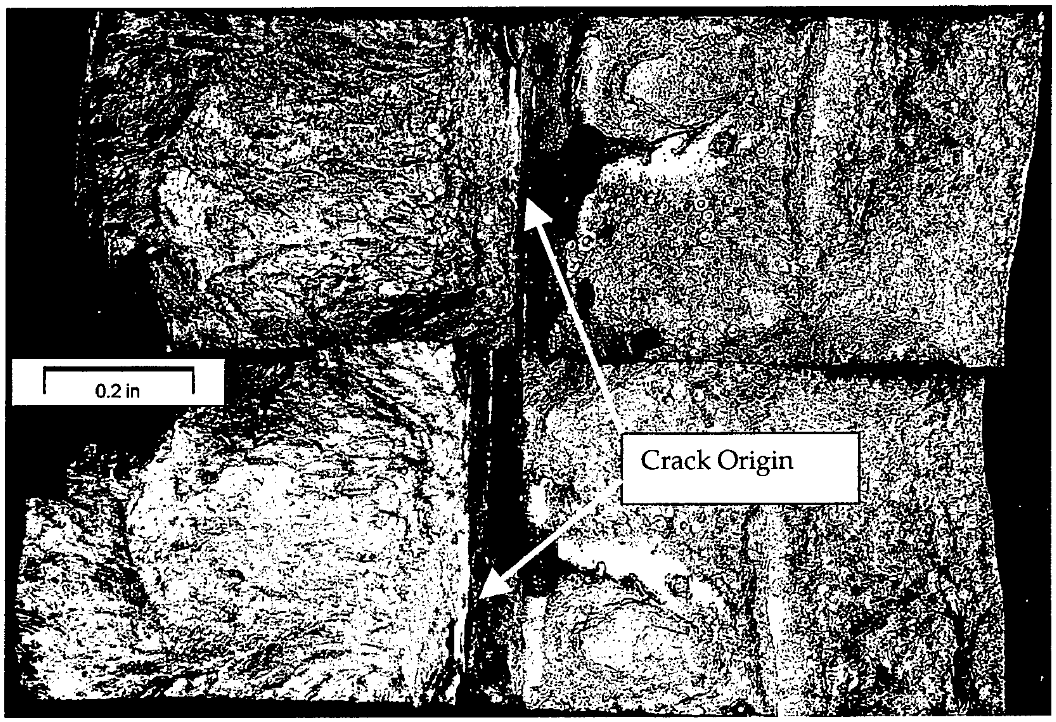

Figure 7. Fracture surfaces of tensile specimen 1.

The break in specimen 2 began at the metal-weld interface and went through the plate thickness. The fracture surfaces, shown in Figure 8, are much more uniform than those shown in Figure 7.

The remainder of the plate was tested ballistically with a fragment simulating projectile (FSP). The details of the test procedure can be found in Burkins et al. (2001). The FSP is a low-aspect-ratio blunt-nose steel projectile with a mass of 54 g. The tests were conducted in Experimental Facility 110, Lethal

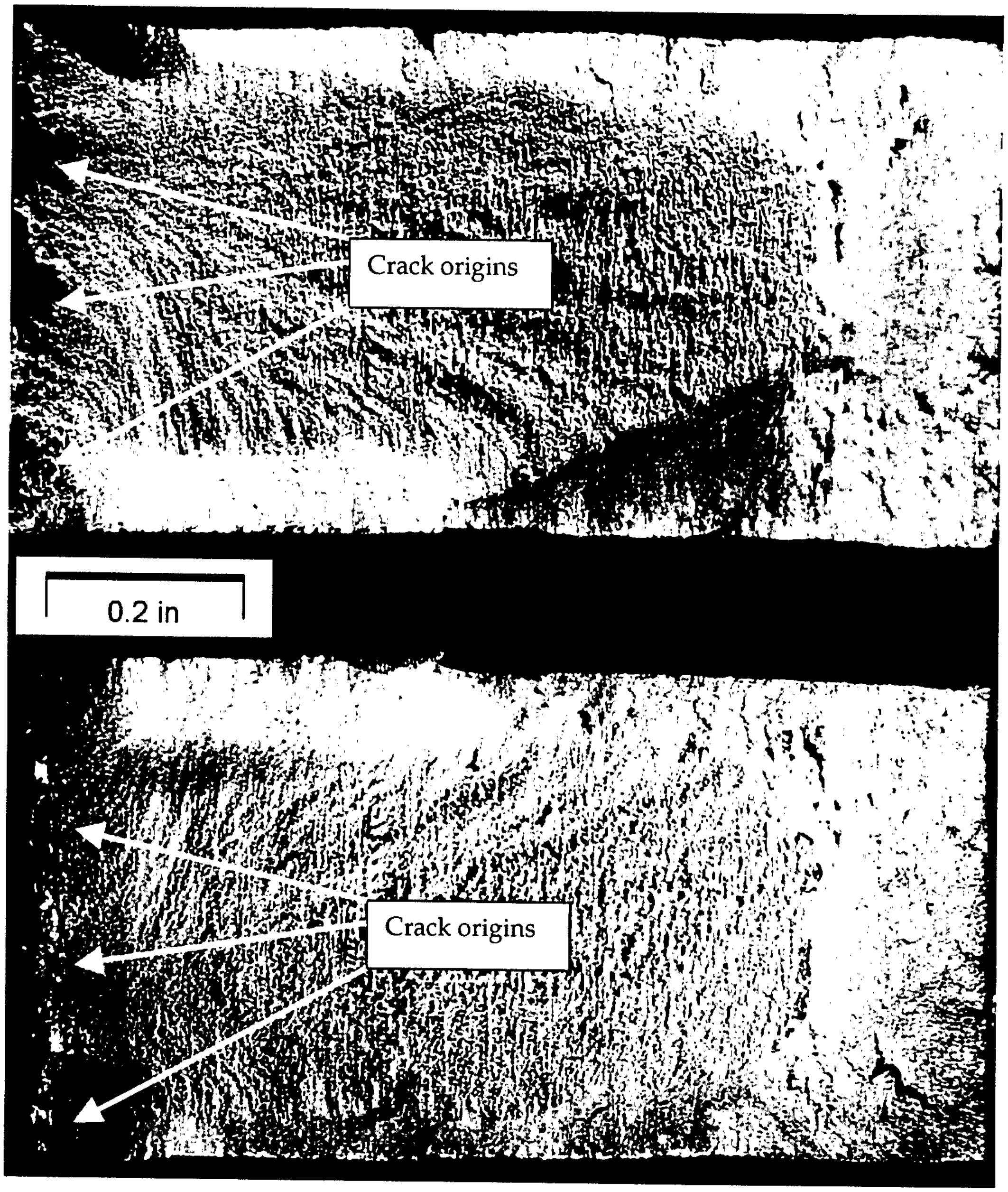

Figure 8. Fracture surfaces of tensile specimen 2.

Mechanisms Branch, Terminal Effects Division, Weapons and Materials Research Directorate, ARL. All impacts were at normal obliquity and a minimum of projectile yaw. The impact point was directly on top of the weld. At this location, the thickness of titanium alloy is ~1.3 in. The test data are shown in Table 5.

The front and back of the plate are shown in Figures 9 and 10.

Table 5. Ballistic test results.

Shot No.	Striking Velocity (m/s)	Pitch (°)	Yaw (°)	Result	Residual Velocity (m/s)	Residual Mass (g)
8906	988	0.5	-1.0	CP	60	—
8907	945	0.5	-0.75	CP	58	29.3
8908	887	0.75	-0.5	CP	43	3.1
8909	837	0.75	-0.5	PP	—	—
8910	866	0.25	-0.75	PP	—	—

Notes: CP = complete penetration; PP = partial penetration.

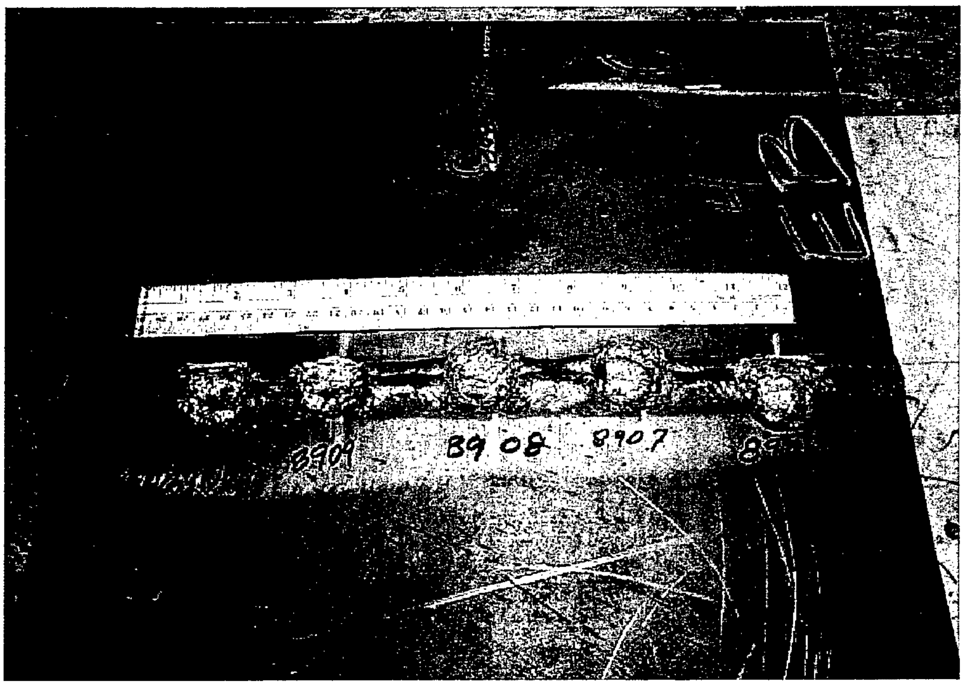

Figure 9. Entrance side of welded plate.

A positive pitch indicates a nose up impact, and a positive yaw indicates the projectile was slanted to the right as one looks downrange. The residual velocity and velocity are associated with the chip or plug thrown from the exit side of the target. In no case did the FSP perforate the target. The chip thrown off as a result of test 8906 was too small to recover and measure. It appeared as a small (2-mm-diameter) fragment on the radiograph behind the target. No chip or plug was thrown off the back of the target as a result of tests 8909 and 8910, although the weld was cracked in a small region behind the impact point. The limit velocity or V50 lies somewhere between 866 and 887 m/s. For comparison purposes, an average of these two numbers is used to provide a rough estimate of the limit velocity/V50 (877 m/s).

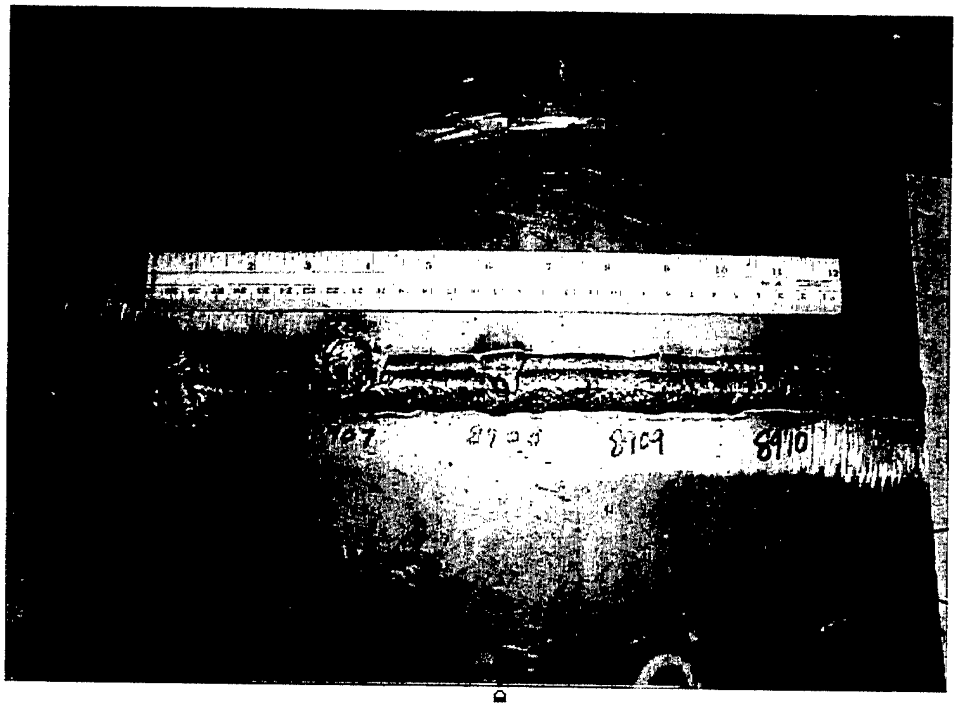

Figure 10. Exit side of welded plate.

3.2 Discussion

In previous work, Burkins et al. (2001) found that the electron beam single melt titanium alloy met the new military specification for titanium alloys and had mechanical properties that were close to the higher quality titanium alloy used for aerospace applications. This is not too surprising considering the fact that the oxygen impurity in the sample they investigated was relatively low (0.17%). It stands to reason that standard welding techniques developed for titanium alloys can be applied to the single melt material.

It is also clear from the results of the first attempt to weld titanium plates that a great deal of care must be taken to shield the weld area with inert gas. The most likely explanation of the cracks that occurred in the 1-, 1 1/2-, and 2 1/2-in plates is that upon start-up of the weld process (after a break in the work), there was not enough argon gas flow to shield the weld from oxygen. The indicators for this conclusion are the following. First, the last bead put down appeared to be much less lustrous than the previous beads, indicating some contamination. Second, the crack in the 1-in plate was almost entirely contained in the last bead put down. It is surmised that the cracks in the other two plates began in the last bead and propagated to the rest of the weld. The welding wire used for the three plates was old, and a chemical analysis revealed that it had a higher than normal hydrogen content. However, a chemical analysis of the weld material did not

confirm a high level of hydrogen. In any event, new wire was used for the second attempt to weld the 1-in plate.

The presence of the weld reduces the mechanical properties of the plate as compared to those of a solid plate made of electron beam single melt titanium alloy. Properties of the 1-in plate with the weld are compared to data from Burkins et al. (2001) in Table 6. Only the values obtained for the sample 2 tensile specimen of the welded plate are used for comparison.

Table 6. Electron beam single melt titanium alloy material property comparison.

Plate Type	Tensile Strength (ksi)	Yield Strength (ksi)	% Elongation	Limit Velocity (m/s)
Welded	131	126	1	877
Solid	149	138	15	1016

Smith et al. (1999) indicate that the strength of the weld metal for standard Ti-6Al-4V should be 140 ksi, using metal-inert gas welding techniques. The same authors quote the elongation for the weld material as 8%. Tensile specimen 1 broke at a low stress due to incomplete weld fusion and is not included in Table 5. Also, the fracture in tensile specimen 2 occurred primarily in the heat-affected zone so that mechanical properties of the weld material by itself were not determined by the tensile test. The low values of elongation and strength for the welded plate (as compared to the solid plate) are consistent with the lower-limit velocity. The plate failure in the ballistic tests was through spall of the back surface of the weld and not by actual perforation of the plate by the fragment simulator.

On a more positive note, it was observed that a crack did not propagate along the weld under repeated impacts of the FSP on the weld material. This fact offers some indication that the weld can withstand repeated shocks. However, a comparison of these results with those obtained from firing at the welded box structure (Grendahl et al. 2001) may not be valid due to the different threat, impact conditions, and target configuration.

4. Task 2

4.1 Procedures and Results

Task 2 involved the out-of-position welding of titanium plates. The goal was to assess the feasibility of welding plates that were not level, such as might be encountered on armored vehicles. The application was for field repair of vehicles containing titanium armor.

Three pairs of plates were prepared for this task. Each single plate was approximately 6 × 6 × 3/8 in. A 30° bevel was cut on one side of each plate with a water jet so that when two plates were brought together to form a 6- × 12-in plate, a V-notch was formed. Before welding, the welding surfaces were polished with a 3M 785C Regalite Polycut Fiber grinding disk and cleaned with acetone. A 2- × 12- × 3/8-in backing plate was tacked welded to the rear of the V-notch in each of the plates just before the welds were made. Astrolite Alloys welding wire (1/16-in diameter) in 3-ft strips was used as the welding medium. Its AMS class was 4956C (Ti 6A1-4V ELI). A stainless steel brush was used to clean the weld area between passes. The welding power source was a Miller Syncrowave Model 351 operating at 124 A and 14 V. Five passes were made on each set of plates.

The shielding gas was argon. A specially made trailing shield was used for the out-of-position welding. Its length was ~3 in, and its width was 1 in. The flow rate of argon through the trailing shield was 30 ft^3/hr.

Two different plate orientations were used: vertical and horizontal. The weld on the horizontal plate was made on the underside of the plate (i.e., overhead). Vertical and horizontal welds were made on plates oriented in the vertical direction.

The backing plate was sawed from each of the plates. As mentioned previously, the welding procedure produced plates that were in the form of a shallow V. This made sawing the backing plate with a band saw relatively easy. However, identical plate thicknesses in the weld areas were not achieved for all the plates. The plates were then digitally x-rayed. The results are shown in Figures 11–13.

There are no obvious flaws or inclusions in any of the welds. The difference in gray scale in each of the figures is due primarily to the difference in plate thickness as a result of sawing off the backing plate. No mechanical tests of the welds were made.

4.2 Discussion

This work provides a positive indicator that field repair of titanium armor structures is possible. However, there are several factors that must be considered that were not addressed here. First, the welds made in the current work were accomplished under depot-like conditions. That is, the welds were made inside a structure and not in the open field. Since it is very important to keep oxygen away from the weld area until the weld has cooled, it may be necessary to use a modified glove box filled with argon to weld in an open area not protected from the wind.

Second, if the armor structure to be repaired is accessible from only one side, it may not be possible to attach a backing plate to the region to be welded. This limits the type of repairs that can be made. For instance, if there is a hole in an

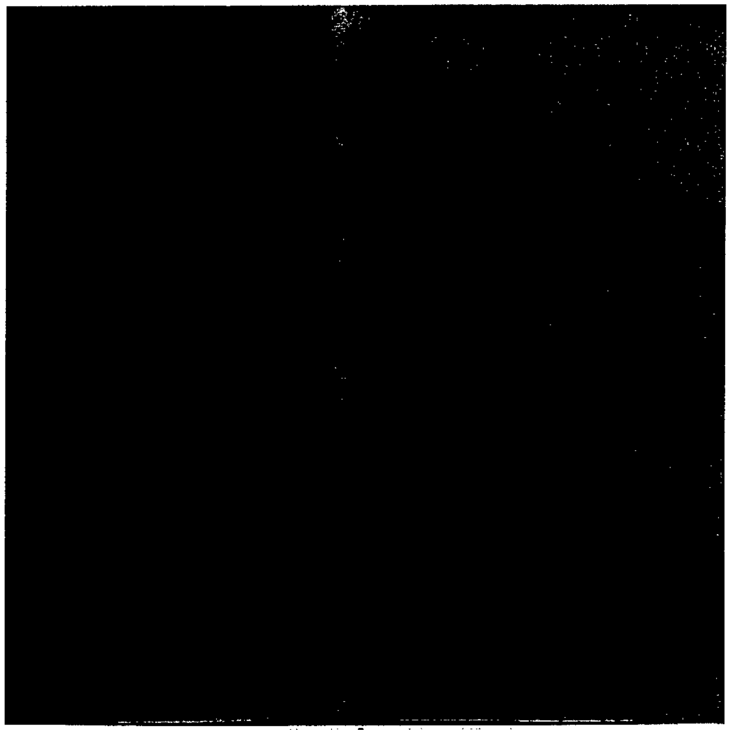

Figure 11. Vertical plate, horizontal weld.

Figure 12. Vertical plate, vertical weld.

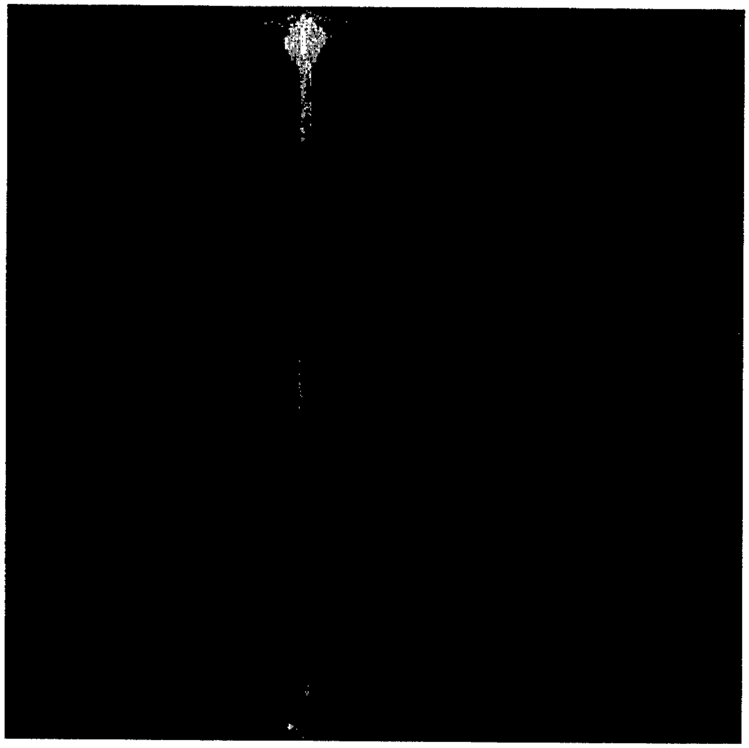

Figure 13. Horizontal plate, overhead weld.

exposed titanium armor plate, a secondary plate might be welded over it from the outside. In this case, the vehicle armor plate itself could act as a backing plate. If there is a substantial crack in an exposed plate, the crack could be filled with weld material. In any case, the field repair of a damaged titanium armor structure is expected to be a temporary fix only. Permanent repairs would have to be made at depot level or at the original equipment manufacturer's facility.

5. Task 5

In comparing the costs of manufactured titanium and steel, both the cost of extraction of the metal from the ore and the processing of the metal into parts contribute to the cost difference. Even though titanium is one of the most plentiful elements on earth, its close affinity to oxygen and its high melting point (relative to aluminum, for example) make extracting titanium from the ore (rutile) expensive. Fabricating parts from titanium stock is also relatively expensive, due to a number of factors that will be discussed. In any event, the cost of titanium in manufactured parts will depend on a number of factors, including source of supply, extraction technology, size of order, application, and processing technology used.

Titanium occurs in nature as titanium dioxide. It is transformed into titanium tetrachloride (tickle) by reaction with chlorine and carbon (coke) at high temperature. The resulting tickle costs $1.48/lb (Gerdemann 2001). From that point, there are several processes that can produce pure titanium. One of the most widely used is the Kroll process that uses magnesium to reduce the tickle to titanium and magnesium chloride. The titanium is left in a porous state called sponge, along with various impurities, including magnesium chloride.

The cost for sponge will vary with market conditions and suppliers. For instance, Crowley (2001) quotes the price of sponge at $4–$5/lb. An even wider range of $3.50–$7/lb for unrefined sponge is quoted by Camanoe Associates (2001). These reflect, to some extent, historical ranges of the price of titanium sponge. More current price information is available from the American Metal Market (2001). A 21 September 2001 news release quotes the price of sponge at $3.33–$4.08. The price of sponge is also dependent on the quality of the product. The numbers shown in Table 7 are a result of sales of titanium sponge from the national stockpile and may not be of the highest quality.

Table 7. Representative cost numbers for titanium sponge.

Date	Amount (lb)	Buyer(s)	Cost per Pound ($)
09/28/00	6,700,000	KB Alloys	1.64
		Monico Alloys	
		RMI Titanium	
		TIMET	
		Specialty Metal Products	
07/20/00	1,000,000	Wah Chang	1.70
		TIMET	
		Goldman Titanium	
05/16/00	105,000	Goldman Titanium	1.30
04/19/00	40,000	Willan Wogen	1.25

Source: Caitlin O'Leary, Defense Logistics Agency, Ft. Belvoir, VA, (703) 767-6753.

Further processing is required to convert the sponge into a usable material. In particular, alloying metals must be added and impurities removed. Titanium alloy is generally made by melting together scrap titanium (at a cost of $2–$3/lb), titanium sponge, and alloying ingredients (e.g., aluminum and vanadium) to produce an ingot. The ingot may be remelted several times to remove impurities. The cost for the original melt is about $1/lb and $0.50/lb for each additional melt (Gerdemann 2001). The final ingot may cost as much as $10/lb (Crowley 2001). A price range quoted in August 2001 by the American Metal Market was $7.50–$8/lb for titanium alloy in ingot form. This should be compared to the $1–$2/lb for armor steel. There was a general reluctance on the

part of titanium producers to quote a specific cost per pound. For instance, Bill Pallante of RMI Titanium* did not wish to quote a price but did say that RMI and ARL were developing a cooperative research and development agreement (CRDA) that would establish a price for titanium to be used for armor applications on ground vehicles. The general consensus was that the price of titanium depended on many variables.

Processing the titanium ingot will add to the cost per pound of the finished part. This is where a lot of the variability for titanium costs is incurred. If an ingot is rolled to produce a plate, there is a certain amount of scrap produced as the edges of the ingot are sheared off in the rolling process. If one starts with a plate-shaped ingot, the loss is less. If there is a great deal of material that needs to be removed in the shaping process, the cost per pound of the finished part can be large, even though much of the scrap can be recycled. A typical price for a finished mill product is $16/lb (Crowley 2001). The August 2001 price quote from American Metal Market is $17–$17.50/lb for rolled plate material.

The use of single melt alloy combined with casting the melted alloy into a shape amenable to rolling into plate has the potential to reduce the cost of titanium alloy armor by up to 30%. This is the goal of a current U.S. Army Manufacturing and Technology (MANTECH) program being conducted by the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) at Picatinny Arsenal, NJ.

One other processing technology should be mentioned for the sake of completeness. This is the process by which titanium alloy powder is directed through a laser beam, melted, and deposited by rastering across a surface to build up a near-net-shape object. Known as laser free-forming, this process might be more economical than machining the part from an ingot, according to Brad Cleveland of AeroMet Corporation.† For instance, laser free-forming could be used to add a small flange or other small protrusion on a large part. The cost of the small amount of added titanium might be $10/lb, but there is an overall cost savings compared to that of machining the flange or protrusion.

One of the major cost drivers for laser free-forming is the cost of the titanium powder. Producing titanium powder from the ingot form can cost as much as $120/lb of powder (Crowley 2001). The Armstrong process may reduce these costs substantially. This process takes the titanium tetrachloride and reduces it to titanium powder directly through interaction with molten sodium in a carefully controlled environment. The titanium can be alloyed in the same process. An optimistic estimate for the powder cost, based on a large production base, is about $7/lb. The powder can be used in a hot isostatic pressure process

---

* RMI Titanium, 1000 Warren Avenue, Niles, OH 44446, (330) 544-7793.

† AeroMet Corporation, 7623 Anagram Drive, Eden Prairie, MN 55344, (612) 974-1801.

to produce fully dense plates. This might add another $1/lb to the cost, making it competitive with mill products (Crowley 2001).

Another process being considered for the production of titanium powder is a hydride-dehydride reaction where titanium hydride is converted into small particles and then is used in a cold spray operation to fabricate near-net-shape parts (Tapphorn and Gabel 1998). The authors estimate that production of near-net-shape parts could be made for as low as $6/lb. However, the authors did not discuss how the titanium powder would be alloyed or how much alloying would increase the price of the final product. In addition, it was not clear from the article if the cost of the initial titanium powder feedstock was factored into the final costs.

One further consideration is the cost to weld parts from titanium alloy mill stock. The cost of welding wire for steel is about $3/lb, whereas the cost of welding wire for titanium alloy can be as high as $100/lb. (The cost for the wire used in this study was $68/lb.) In addition, there is extra cost associated with shielding the welding area with an inert gas in the case of titanium alloy welding.

In summary, the cost per pound of finished titanium parts is a function of many variables. Consequently, it is difficult to pin down an exact figure. The factors that go into determining the price are as follows:

- cost of titanium tetrachloride;
- cost of titanium sponge, titanium scrap, and alloying elements;
- number of melts and refining process;
- requirements for low oxygen content;
- process used to produce usable stock (casting, laser free-forming, and powder metallurgy processing);
- cost of oxygen free environment for heat treatment/annealing/welding;
- loss of material during the part shaping; amount of scrap recycled;
- cost of machining, forming, or welding/joining; and
- market conditions (supply and demand).

A reasonable estimate for finished parts (primarily plate) made from titanium alloy to be used as armor material would be in the $15–$20/lb range, based on all the information previously provided, using current technology. New technologies have the potential to reduce the cost of titanium armor to around $10/lb. However, it is unlikely that costs can be reduced below this figure in the foreseeable future.

INTENTIONALLY LEFT BLANK.

6. References

American Metal Market (AMM). <http://www.amm.com/index2.htm>. 2001

American Society for Testing and Materials (ASTM). "Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate." ASTM B265-99, West Conshohocken, PA, July 1999.

Burkins, M., M. Wells, J. Fanning, and B. Roopchand. "The Mechanical and Ballistic Properties of an Electron Beam Single Melt of Ti-6Al-4V Plate." ARL-MR-515, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 2001.

Camanoe Associates. "The Role of Titanium in the Automobile." White paper, Northwest Alliance for Transportation Technology, Cambridge, MA, June 2001.

Crowley, G. "The Armstrong Titanium Extraction Process." White paper, International Titanium Powder, LLC, Chicago, IL, October 2001.

Gerdemann, S. J. "Titanium Process Technologies." *Advanced Materials and Processes*, pp. 41–43, July 2001.

Grendahl, S., D. Snoha, and B. Roopchand. "Fabrication and Evaluation of Welded Ti-6Al-4V Test Sections." ARL-TR-2533, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 2001.

Harris, I. D. "Titanium Alloy Welding Procedure Qualification." Project No. 44081GDE, Edison Welding Institute, Columbus, OH, 9 January 2001.

Roopchand, B. "Titanium Trims Army Ground Vehicle Weight." Proceedings of the 17th Annual Conference, International Titanium Association, Las Vegas, NV, 30 September–3 October 2001a.

Roopchand, B. "Manufacturing Technology for Ti-6Al-4V Gunmount Cradle." Proceedings of the Defense Manufacturing Conference (DMC2001), Las Vegas, NV, 26–29 November 2001b.

Smith, L. S., P. Threadgill, and M. Gitos. *Welding Titanium–A Designer and Users Handbook*. Cambridge, England: The Welding Institute, May 1999.

Snoha, D. J., S. M. Grendahl, M. G. H. Wells, and M. E. Wells. "An Evaluation of Former Soviet Union Welding Processes on Commercially Pure Titanium." ARL-TR-2587, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, December 2001.

Society of Automotive Engineers. *Titanium Alloy Welding Wire, GAI-4V Extra-Low Interstitial*. AMS 4956C, Warrendale, PA, 1994.

Tapphorn, R. M., and H. Gabel. "The Solid-State Spray Forming of Low-Oxide Titanium Components." *Journal of Metals*, pp. 45, 46, and 76, September 1998.

U.S. Department of Defense. *Titanium and Titanium Alloy Sheet, Strip, and Plate.* MIL-T-9046J, Washington, DC, 1999.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDR&E(R) DR R J TREW 3800 DEFENSE PENTAGON WASHINGTON DC 20301-3800
1	COMMANDING GENERAL US ARMY MATERIEL CMD AMCRDA TF 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D DR D SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI IS T 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
2	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	CRUSADER OPM SFAE GCS CRE B ROOPCHAND BLDG 171 PICATINNY ARSENAL NJ 07806-5000
	ABERDEEN PROVING GROUND
15	DIR USARL AMSRL WM MC R ADLER J BEATTY J MONTGOMERY J WELLS AMSRL WM MD M BURKINS V CHAMPAGNE W DE ROSSET R DOWDING W GREEN S GRENDAHL M PEPI W ROY D SNOHA W ZIEGLER AMSRL WM TC E DEAL

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2002	Final, 1997–2002

4. TITLE AND SUBTITLE
Welding of Electron Beam Single Melt Ti-6Al-4V Plate

5. FUNDING NUMBERS
PE0708045A
DE25

6. AUTHOR(S)
William S. de Rosset, Matthew Burkins, and Brijmohan Roopchand*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-MR-539

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
U.S. Army Tank-automotive and Armaments Command, Warren, MI 48397

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*U.S. Army Tank-automotive and Armaments Command, Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ 07806-5000

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Single melt titanium alloy is being considered for use as armor in ground combat vehicles due to its lower cost relative to aerospace-grade material. This report examines welding issues associated with fabricating titanium alloy plate. In particular, the quality of welded single melt material was investigated as well as the possibility of out-of-position welding of standard titanium alloy. The initial results indicate that single melt material can be welded using standard techniques. Out-of-position welding can be accomplished under controlled conditions, but further process development would be needed to be able to repair titanium alloy armor in the field.

14. SUBJECT TERMS
single melt titanium, titanium welding procedures, ballistic tests of titanium welds, titanium weld properties, out-of-position welding of titanium, titanium production costs

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.